

Abstract. The interpretation of high proper motion white dwarfs detected by Oppenheimer et al. (2001) was the start of a tough controversy. While the discoverers identify a large fraction of their findings as dark halo members, others interpret the same sample as essentially made of disc and/or thick disc stars. We use the comprehensive description of galactic stellar populations provided by the "Besançon" model to produce a realistic simulation of Oppenheimer et al. data, including all observational selections and calibration biases. The conclusion is unambiguous: Thick disc white dwarfs resulting from ordinary hypotheses on the local density and kinematics are sufficient to explain the observed objects, there is no need for halo white dwarfs. This conclusion is robust to reasonable changes in model ingredients. The main cause of the misinterpretation seems to be that the velocity distribution of a proper motion selected star sample is severely biased in favour of high velocities. This has been neglected in previous analyses. Obviously this does not prove that no such objects like halo white dwarfs can exist, but Oppenheimer et al. observations drive their possible contribution in the dark matter halo down to an extremely low fraction.

Key words: Cosmology: Dark matter – Galaxy: structure
– Galaxy: stellar content – Galaxy: general

On high proper motion white dwarfs from photographic surveys

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1. Introduction

In a recent paper, Oppenheimer et al. (2001) (hereafter OHDHS) give evidence for a large number of faint white dwarfs detected in digitized photographic plates from the SuperCOSMOS Sky Survey¹. Their interpretation of these stars as dark halo members was the start of a controversy. While Reid et al. (2001) and more recently Graff (2001) interpret OHDHS stars as the high velocity tail of the disc/thick disc populations, Koopmans & Blandford (2001) argue that there is a statistically significant break in the velocity distribution, which they interpret as the thick disc/halo break. Eventually, they propose a dynamical mechanism to produce these “halo” objects out of the disc. Another line of arguments has been developed by Gibson & Flynn (2001) who point out a number of biases in OHDHS analysis all adding up to produce an overestimation of the local density of halo white dwarfs, but the authors do not question their nature. In addition, Hansen (2001) finds a similar age distribution for this population as those in the thin disc white dwarf population. In order to clarify the situation, we use the Besançon model of stellar populations in the Milky Way to simulate OHDHS observations. In the next section we describe model hypothesis and the construction of the simulated sample, the third section being dedicated to the discussion and conclusions.

2. Simulations

We have performed simulations from the Besançon galactic model using the following assessment: disc stars are assumed to have ages from 0 to 10 Gyr, with appropriate kinematics as a function of age (Haywood et al., 1997). The density laws are Einasto discs, which are close to sech^2 vertically (Bienaymé et al., 1987a,b). The white dwarf luminosity function is from Sion & Liebert (1977)

and the photometry is derived from Bergeron et al. (1995) model atmosphere. The ellipticities of these components are a function of age, and constrained by the galactic potential through the Boltzmann equation. The average kinematics of white dwarfs in a volume limited sample in the solar neighbourhood result in a velocity ellipsoid (42.1,27.2,17.2) and an asymmetric drift of 16.6 km s⁻¹.

The thick disc population is modeled as originating from a single epoch of star formation. The adopted thick disc density law is described in Reylé & Robin (2001), as fitted on large sets of available star counts. The local density is 10⁻³ pc⁻³ ($M_V < 8$), that is about 6% of the disc local density. In order to insure derivability in the plane, the density law is a parabola near the plane ($z < 337$ pc), then an exponential of scale height 850 pc further out from the plane.

The white dwarf luminosity function (hereafter WDLF) of the thick disc has been computed by Garcia-Berro (private communication) from the model of Isern et al. (1998) assuming a Salpeter IMF and an age of 12 Gyr. We attempted to normalise the WDLF by computing the number of white dwarfs relative to main sequence stars, assuming that all stars with a mass greater than the mass at the turnoff ($M_{TO} = 0.83 M_\odot$) are now white dwarfs. We consider a two slope IMF, the lower mass parts being constrained by available star counts (Reylé & Robin, 2001) accounting for a binary correction:

$$\begin{aligned} dN/dm &\propto m^{-2.35}; M_{TO} < m < 8M_\odot \\ dN/dm &\propto m^{-0.75}; 0.1 < m < M_{TO} \end{aligned}$$

The ratio of white dwarfs to main sequence stars is therefore:

$$\frac{N_{WD}}{N_{SP}} = \frac{\int_{M_{TO}}^{8M_\odot} m^{-2.35} dm}{\int_{0.1M_\odot}^{M_{TO}} m^{-0.75} dm} = 0.58$$

However, it appears that the predicted number of thick disc white dwarfs, with these assumptions, is much higher than the number of observed white dwarfs in the OHDHS sample. Several reasons could be invoked: First, we do not know how the OHDHS sample is complete, specially near the limiting magnitude. Second, hypotheses which

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have led to the estimation of the thick disc WDLF have not been tested yet because these stars are not identified as such in current white dwarfs samples : Uncertainties remain on the IMF slope (at high mass, with no observational constraints, we have chosen the conservative Salpeter IMF, while at low mass an IMF slope $\alpha = 1$, still within our error bars, drives down the fraction to 0.42). Uncertainties remain also on the star formation history, that may be more complex than a single burst. These reasons led us to normalize the thick disc WDLF in order to be in agreement with the OHDHS sample: the fraction of white dwarfs over sub-turnoff stars drops down to 20%, about the value of Hansen (2001), corresponding to a local density of 5×10^{-4} stars pc^{-3} . This normalisation is also in agreement with the number of white dwarfs in the expanded LHS white dwarfs sample (Liebert et al., 1999).

The velocity ellipsoid of the thick disc is constrained by photo-astrometric survey in several galactic directions (Ojha et al., 1996) to be (67,51,42) while the asymmetric drift is 89 km s^{-1} .

Halo white dwarfs are modeled assuming that the dark halo is filled with ancient white dwarfs with a certain factor f . The dark halo local density is $8.10^{-3} \text{ M}_{\odot} \text{pc}^{-3}$ from dynamical constraints. Hence the local density of halo white dwarfs is assumed to be f times this value. As a first guess compatible with microlensing constraints, we set $f=0.1$ in this simulation. We use Bergeron et al. (1995) model atmosphere for hydrogen white dwarfs of mass 0.6 M_{\odot} to the turnover ($M_V < 17$), and Chabrier et al. (2000) models for the cooler part of the sequence. The halo white dwarfs luminosity function has been computed by Isern et al. (1998) with the *ad hoc* Chabrier (1999) IMF and an age of 12 or 14 Gyr. The space velocities are computed with the kinematics of the usual spheroid, a velocity ellipsoid (131,106,85) and a null rotation, the LSR rotational velocity being 229 km s^{-1} (Bienaymé et al., 1987a).

Simulation is made by transforming the standard Johnson-Cousins system to the observed one using the equations given in the SuperCOSMOS Sky Survey description:

$$B_J = B - 0.28 \times (B - V); \text{ for } -0.1 < B - V < 1.6$$

$$R59F = R - 0.006 - 0.059 \times (R - I) + 0.112 \times (R - I)^2 + 0.0238 \times (R - I)^3$$

The selection of the simulated sample has been done strictly following the OHDHS process. We simulate a field of 4165 deg^2 at the south galactic cap. We select a sample of stars with $R59F \leq 19.45$, and proper motions in the range 0.33 to $3'' \text{ yr}^{-1}$, assuming a mean error of $0.04'' \text{ yr}^{-1}$. In order to reproduce the space velocities deduced by OHDHS, from the resulting sample, we compute the reduced proper motions, absolute magnitudes M_{B_J} , distances and space velocities U and V using their formulae.

3. Results and discussion

Fig.1a reproduces the observed distribution of the OHDHS WD sample in the (U,V) space. The ellipses indicate the 1σ and 2σ velocity dispersions as defined by OHDHS for the old disc (right) and the halo (left). Objects out of the 2σ old disc ellipse are interpreted as halo white dwarfs by OHDHS (squares with boxes). This figure can be compared with the simulated distribution of the selected white dwarfs represented in fig.1b. The disc is coded with pluses, the thick disc with dots, and the spheroid with stars. Ellipses are the same as in fig.1a for comparison.

The vast majority of OHDHS white dwarfs out of the 2σ old disc ellipse can in fact be interpreted as thick disc white dwarfs, as expected from ordinary hypotheses on the local density and kinematics of the thick disc white dwarfs, although it is not possible to be sure that none of these white dwarfs own to the dark halo. Hansen (2001) argues that the OHDHS white dwarfs are not old enough to account for the thick disc population, given that most of the white dwarfs in the thick disc should be fainter in the case of a single burst of star formation in the thick disc 12 Gyr ago. However, the simulation shows that, even in the burst case, the number of younger white dwarfs in the thick disc remains large enough to explain the OHDHS sample. They come from stars for which the time spent on the main sequence is not negligible. Actually, very few of the simulated stars are beyond the turnover in the white dwarfs color-magnitude diagram.

Another difference appears in fig.1: considering an age of 12 Gyr for the halo white dwarfs and a fraction $f = 0.1$, 10 objects are expected to have $V < -400 \text{ km s}^{-1}$. None of the OHDHS white dwarfs are present in this part of the diagram, indicating that the halo white dwarf local density is no more than 1% of the dark halo local density. However, this upper-limit remains uncertain as the completeness of the OHDHS sample is not precisely determined. Furthermore, if considering an halo age of 14 Gyr, the expected number falls down to 2.

Two biases can be identified in the OHDHS study. A first bias comes from the photometric distances. They are determined from a linear colour-magnitude relation, with uncertainties around 20%. Among the nearest simulated stars ($d < 100 \text{ pc}$), a few stars are old halo white dwarfs which are close to the turnover in the colour-magnitude diagram: they continue to cool and fade away but their B_J - $R59F$ colour remains constant. For these stars, the photometric parallax derived from the linear relation is not valid anymore. Their intrinsic luminosity and consequently their distance are overestimated. This leads to an overestimation of their V velocity. The number of stars affected by this bias is small. But it affects specially the white dwarfs after the turnover, that is the stars one are looking for to explain the dark matter halo.

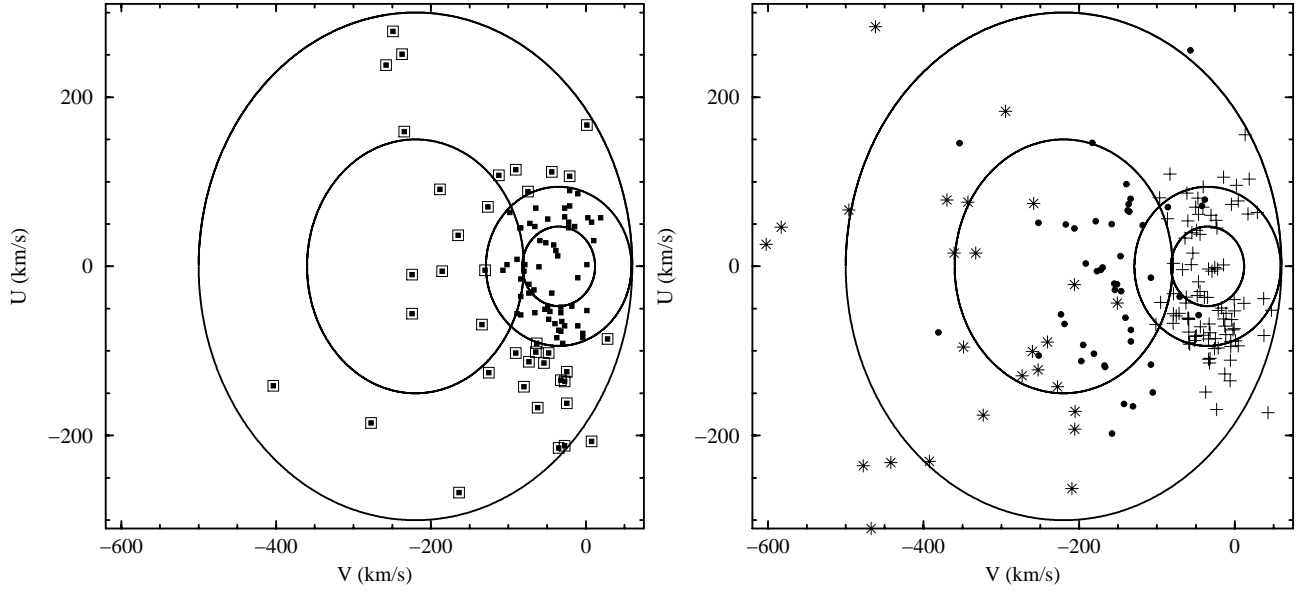


Fig. 1. Velocity space distribution of white dwarfs in the Oppenheimer et al. (2001) sample: a. Original observations. Objects with boxes are interpreted as halo stars. b. Simulation with a white dwarf local density being 10% ($f = 0.1$) of the dark halo local density, and an age of 12 Gyr. Plus: disc, circle: thick disc, star: halo.

A strong second bias comes from the selection of high proper motion stars which isolates a high velocity tail of each population. Ellipses in fig.1 characterize the halo kinematics of a complete sample, but are incorrect for a high proper motion sample. Koopmans & Blandford (2001) conclusions are affected by the same bias effect. By using a maximum likelihood algorithm, they fitted a two maxwellian component kinematical model on the observed U, V velocity distribution. Their analysis give convincing evidence that the OHDHS sample splits into two well separate components. The first component is characterized by a rotational lag of 50^{+10}_{-11} km s $^{-1}$ and $\sigma_U = 62^{+8}_{-10}$ km s $^{-1}$. The second one is characterized by a lag of 176^{+102}_{-80} km s $^{-1}$ and $\sigma_U = 150^{+80}_{-40}$ km s $^{-1}$. They assimilate the first component with the thick disc and consistently the second one with the halo. While the statistical separation seems unquestionable, the population diagnostic requires more care: the estimated average rotation and velocity dispersion are not those of a volume selected sample but those of a proper motion and apparent magnitude selected sample.

The simulated sample also can be separated in two distinct populations and it well reproduces the observed dispersions and rotation lag. However, it appears that what Koopmans & Blandford (2001) interpret as a thick disc population originate from the disc in the simulation, while their “halo” population come from a thick disc initial distribution.

As shown in table 1, due to the observational biases in the sample, the mean asymmetric drift of the resulting sample is much larger than the normal value for a complete sample in the solar neighbourhood. The values obtained by Koopmans & Blandford (2001) for the first and second

Table 1. Rotational lag and velocity dispersion σ_U for disc, thick disc and halo white dwarfs. Values in a complete sample are those in the original model. Values from the selected sample come from the simulation with the high proper motion and apparent magnitude selections. In the selected sample the computed velocity dispersion and lag are about twice what it would be in a complete sample.

		complete sample	selected sample
lag	disc	16.6 km s $^{-1}$	35 km s $^{-1}$
	thick disc	89 km s $^{-1}$	146 km s $^{-1}$
	halo	229 km s $^{-1}$	344 km s $^{-1}$
σ_U	disc	42.1 km s $^{-1}$	71 km s $^{-1}$
	thick disc	67 km s $^{-1}$	100 km s $^{-1}$
	halo	131 km s $^{-1}$	210 km s $^{-1}$

components are compatible with disc and thick disc kinematics, respectively. The expected values for halo white dwarfs are also given in table 1. There are much larger than the values found by OHDHS and Koopmans, implying that the halo population cannot dominate the sample.

It should also be noted that, even if a large uncertainty remains on the true local density of thick disc white dwarfs, it does not change the conclusion which is mainly based on the velocity characteristics of the sample.

4. Conclusions

The simulated sample, undergoing all observational bias, gives an unambiguous result: the evidence for two separated populations given by Koopmans & Blandford (2001) turns out to reflect the disc/thick disc separation, while Oppenheimer et al. (2001) high velocity white dwarfs can

be safely interpreted as thick disc stars. The OHDHS sample has been misinterpreted because the bias introduced by the selection of high proper motions has been neglected (including in Koopmans analysis). Although some of the stars in the sample may be part of the halo, it is not necessary to call for exotic objects such as white dwarfs in the dark halo. However, this sample provides a direct observation of thick disc white dwarfs. It can help in deriving a luminosity function of these stars which has still very few constraints and which is an important clue in the understanding of the Milky Way history.

The simulation also shows that a true halo WD sample would have much larger velocity dispersions than the OHDHS sample. The number of expected candidates with a V velocity less than -400 km/s, compared with the null detection, implies that the fraction of dark matter halo made of such objects is less than 1% (for a 12 Gyr halo).

In a more general way, this study shows that care must be taken when one tries to interpret the nature of high proper motion white dwarfs in photographic surveys (e.g. Knox et al. (1999); Ibata et al. (2000); Monet et al. (2000)), as the thick disc population is a non-negligible part of high proper motion selected sample, and as thick disc white dwarfs cannot be easily distinguished from halo white dwarfs. As also shown by Crézé et al. (2001), the search for halo white dwarfs needs to be performed in deeper astrometric surveys, when the thick disc becomes non dominant over the expected halo white dwarfs population in high proper motion selected samples.

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